JPL D-16404

OBTAINING SOLUTIONS TO RADIATION- AND PLASMA-INDUCED FAILURE MODES FROM PHYSICS

Dr. A. Robb Frederickson
Jet Propulsion Laboratory, California Institute of Technology
18 September 1998

ABSTRACT

A number of performance-limiting **spacecraft** problems will be qualitatively discussed: Spacecraft Charging, Deep Dielectric Charging, Solar Cell **Arcing**, Antenna Sparking, **High Voltage** Power Shorts, Radiation-induced Defects in Semiconductors, and Degradation of Electronic Devices. A search through the applied atomic physics literature finds new/old paths to solutions. The solutions apply at many levels from the device design level up to system integration and operation. A few examples will be used to illustrate the process of finding solutions in physics. For example, thick **insulator breakdown** involves the physics of atomic electronic transitions, bond breakage and gas evolution, electric field enhancement, and **discharge** of voltage through a conducting gas/plasma. Breakdown may be prevented by controlling any one of the physical processes. At the system level, the same breakdown problem can be controlled by: designing the system to minimize electric energy storage, interrupting the gas "connections" (this solution has been applied on DS1), slowing the gas avalanche, or decreasing sensitivities to the electromagnetic pulse. A second example comes from the recent Galileo Gyroscope Anomaly. Here the spacecraft operations were reprogrammed, hopefully in order to produce radiation-induced annealing of the damage generated by prior irradiation in an electronic device. Radiation-induced annealing results from the physics of bond breaking and localized phonons.

From the masthead I could see
on the Horizon, a place for me.
So I built a machine with a vision its own
which carried me to places unknown.

radiation
plasma
statecharge
radiation effects

This talk was presented on Sept. 18,1998 at the Jet Propulsion Laboratory, Pasadena, CA.

Radiation and hot plasma induce a variety of engineering failure modes in spacecraft systems. Several failure modes, physical phenomena, engineering design principles and spacecraft applications will be discussed.

FAILURE MODES: Descriptions of the failure of a device or system.
PHYSICAL PHENOMENA: The physical process by which the failure was caused.
ENGINEERING DESIGN PRINCIPLES: Procedures for design of systems so that probability of failure is reduced.
SPACECRAFT APPLICATIONS: Specific examples where knowledge of both physical phenomena and failure modes allows one to generate design principles to improve spacecraft.

FAILURE MODES

Spacecraft Charging, Deep Dielectric Charging, High Voltage Power Shorts, Radiation-induced Defects in Semiconductors, Solar Cell Degradation, Solar Cell Arcing, Single Event Effects, Antenna Sparking, Total Dose Electronic Device Failure.

PHYSICAL PHENOMENA

Radiation Transport, Charge Storage in Insulators, Insulator Breakdown, Secondary Electron Emission, Insulator Discharge Phenomena, Paschen Discharge, High-field Conduction, Electric Field Enhancement, Electron-Hole Recombination, Semiconductor Defect Structure and Diffusion, Annealing.

ENGINEERING GUIDELINES

Radiation Tolerant System Design, System Design to Accept Spacecraft Charging, Leaky Insulators Instead of Good Insulators, Rewire the Solar Arrays, Operate the System to Minimize Degradation, Remove Sources of SEE, System Design for Radiation-induced Discharge Pulses, Layout of Wire Bundles.

CASE STUDY METHOD

Failure Phenomena Will Be Described
Using the Case Study Method

THREE PROBLEMS (CASES) WILL BE DISCUSSED:

I.   Solar Cell Electric Breakdown (DS1)

II.   Static Charging/Discharging Inside Spacecraft (Anomalies)

III.   Radiation Damage and Recovery in Electronics (Galileo)

PROBLEM #1, SOLAR CELL ELECTRIC BREAKDOWN FAILURE MODES

Flight solar arrays are now experiencing arcing and short circuits operating at 80 volts, yet ground tests found no problems below 200 volts. The problem is caused by plasma and is enhanced by high-energy radiation. The engineering ground tests prior to flight on real solar arrays found no problems because they did not encompass all of the physical phenomena that can happen. Physics and lab experiments provide clues to the sources of the problem, and potential cures.

Why were these phenomena not found in ground testing with plasma prior to flight?

a) Testers did not know of sympathetic arc coupling.
b) Testers did not know the voltage/current at which arcs are sustained.
c) Extra work is required to simulate solar cell-generated voltage during tests.
d) The test runs for hours, but space runs for years.
e) Inter-wire gap width is somewhat critical, but was not tested for.
f) The thinking during testing concentrated on a physical phenomena called "snapover" and not on physics of failure.
g) Testers were not experienced in high voltage phenomena.

Failure Modes usually involve the occurrence of a sequence of physical phenomena. The phenomena least understood often contain the seeds for solutions, probably because they have been overlooked during system design and test.

After the flight experience, short circuits were reproduced in the laboratory by adding the phenomena of spacecraft charging to the test method. The array segment under test was biased to −300 volts in the plasma and arcs quickly formed and shorted the array. After a period of sustained arc, the kapton substrate became permanently conductive and shorted the array in the absence of the arc.

BUT SIMILAR SHORTS CAN BE CAUSED BY OTHER PHENOMENA

TYPES OF SHORT CIRCUITS AND ARCS

ELECTRODE CORONA - The electric field at an electrode surface is large enough to ionize adjacent gas, or to cause gas to be emitted and subsequently ionized. The ionized gas easily conducts current. This is not likely to apply in space. It is mentioned to orient the reader.

PASCHEN/TOWNSEND DISCHARGE - Free electrons in a diffuse gas gain sufficient energy in the applied electric field to ionize the atoms that it impacts. The resulting ions and electrons are accelerated to produce further ionization, resulting in a conductive plasma. The details of a diffuse gas discharge are complex. [1]

LIGHTNING BOLT - The familiar lightning bolt can form in gas, in liquids, and in solids. If it passes entirely through the medium and connects to the electrodes, a very low impedance plasma channel is formed. Low impedance plasma channels are the most common cause of thick insulation failure.

The prior phenomena are put to good use in: voltage regulator tubes, gas lamps, high voltage switches, pulsed x-ray sources, lightning arrestors, thyrotrons, HV rectifiers, etc (and spark gap transmitters).

STRUCTURAL CHANGE - An insulating material can be changed into a conductive material by application of light, heat, high electric field, or impurities.

A MYSTERY – STATIC ELECTRICAL BREAKDOWN

I have not seen a satisfactory explanation for spontaneous breakdown in insulating media when the voltage source has high internal impedance. Certainly, when a high voltage battery is applied to a thin insulator, the continued flow of current can raise the temperature of the insulator to form a gas breakdown channel. However, based on current knowledge, a static electric field should be slowly dissipated by high field conduction processes in the insulator. Instead, high fields are sustained nearly permanently in insulators simply by the application of static space charge.

Spontaneously, tiny lightning bolts called partial discharge pulses form in the insulator, or at its surface, to create electric pulses on attached electrodes. Rarely is the insulator harmed by the partial discharge, and most of the space charge remains undisturbed. By some mechanism related to flaws, the localized electric field increases and quickly evolves into a tiny local partial discharge event, and emits a flash of light. When the gross surrounding electric field is also large enough, the spontaneous event may propagate over long distances within the insulator and generate a discharge tree.

The mystery occurs at the moment when the local electric field begins to form a lightning bolt. For some reason, instead of dissipating, the electric field concentrates and amplifies at a point where atoms begin to self ionize to form a seed plasma. Once formed, the plasma extends into a bolt with its own sharp point where the field is amplified. Typically, at a sharp conductive point the field is amplified by a factor of 100. At the tip, the high field continues to strip valence electrons and cause the plasma bolt to grow. One can force the initiation of a bolt by striking the insulator with a sharp needle, or by embedding needles in the insulator. The exact conditions for the initial formation of the bolt are not understood. But macroscopic field strength must be at least 1×10^5 V/cm for the bolt to form and begin propagating.

ELECTRIC FIELD REGIMES IN SOLIDS:

ABOVE 10^7 V/cm (1-Volt/Atom)

Electrons are rapidly stripped from the valence states, and accelerated in the conduction band. Electron tunneling evolves into electron avalanching and/or into severe phonon and plasmon generation. Thick materials "vaporize" while thin layers simply liberate their electrons. Useful applications include scanning tunneling microscopy, field emission cathodes, and field emission surface microscopy wherein the high field is applied to a few atoms at a time.

BETWEEN 10^6 V/cm and 10^7 V/cm

Perfect hard materials (with no flaws) can withstand such fields, but surfaces provide flaws such that useful insulators are difficult to design in this region. However, such stresses can be withstood for seconds before localized field enhancement initiates failure.

Soft materials are challenged by polarization of molecules, migration of ions, electrochemistry, and may experience molecular breakup to become "vaporized". Failure occurs rapidly, and repeated application of very brief stresses ages the material.

BETWEEN 10^5 V/cm and 10^6 V/cm

This regime exceeds the handbook tabulations for insulator strength which are based on long term (years) performance requirements for constant service. Never the less, many insulators work reliably in this range (MOS devices, ceramic insulators, graded polymers). Control of flaws is required so that localized field enhancement does not develop. Charge injection at electrodes, or by radiation and plasma, may lead to ultimate failure.

BELOW 10^5 V/cm

Such field strength provides negligible stress to materials. For example, diffusion potential alone at junctions provides 104 V/cm without ill effect. Negligible charge is injected at electrode interfaces, and localized field enhancement is held to low levels by relaxation caused by thermally activated electronic conduction. Practical insulators are generally designed to perform at these stresses.

FIRST BREAKDOWN PROCESS: ELECTRON IRRADIATION
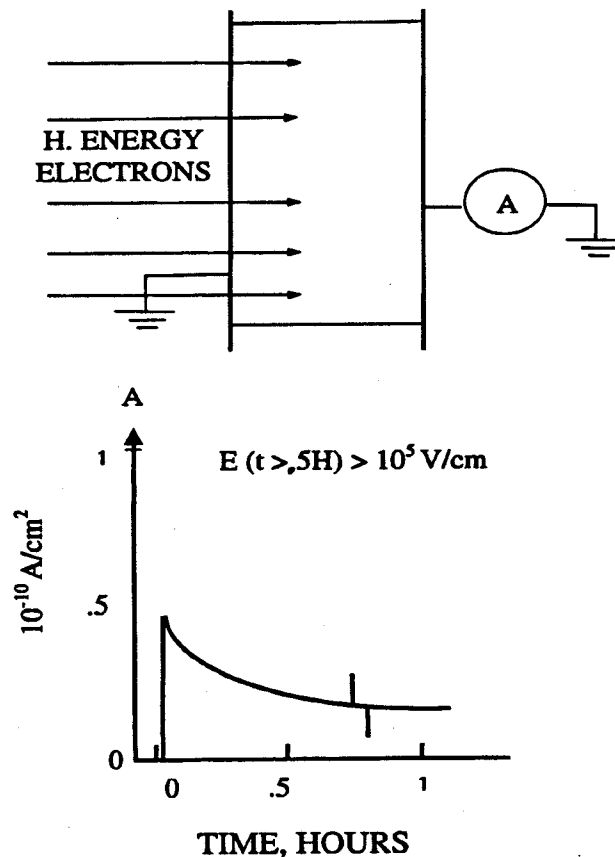
AS THE ELECTRONS IRRADIATE AND STOP IN THE INSULATOR, THE ELECTRIC FIELD GROWS. KNOWING THE PENETRATION DEPTH OF THE ELECTRONS, WE CAN CALCULATE THE ELECTRIC FIELD PROFILE. THE PARTIAL DISCHARGES BEGIN TO OCCUR WHEN THE ELECTRIC FIELD EXCEEDS 10^5 V/cm, or 10^7 V/m. THE PARTIAL DISCHARGES CAN BE THE SEEDS FOR FULL BREAKDOWN.

The analysis of electron beam charging of insulators is now a mature field. [2] For short irradiations where the electron beam provides the most current one finds good agreement between calculation of electric field and experiment. At long times where conduction processes may strongly alter the distribution of charge, one cannot predict the electric fields from analysis. This is because conduction in insulators is usually not well known.
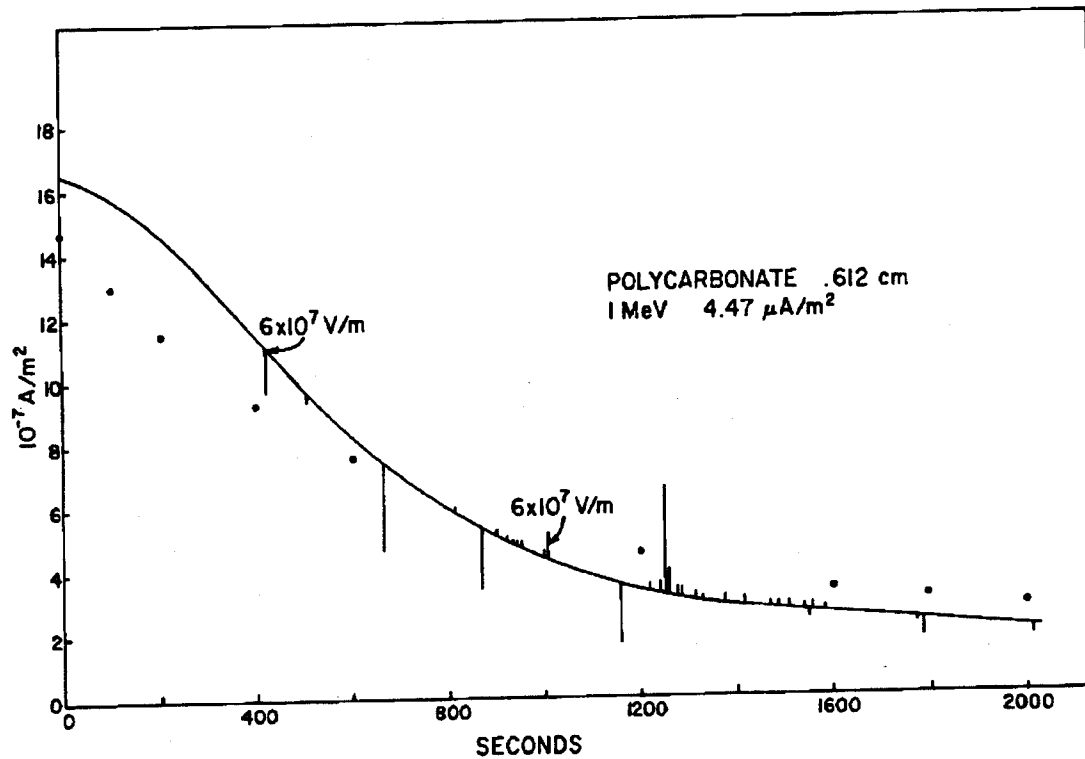
As in most clear materials, the partial discharges in polycarbonate occur occasionally. In this case the electron flux is effectively at least 10 to 100 times the worst case possible in Earth's environment. The results in this figure, and the next are fully discussed in [3]. Each of the vertical spikes is a partial discharge created by a small lightning bolt in the insulator. Each discharge is partial in that it reduces the energy in the electric field to a negligible degree. A typical spike represents about 10E-11 coulomb-volt.

POLYPHENYLENE SULFIDE
.607 cm   .6 MeV
5 μA/m²

1 x 10⁷ V/m

2x10⁸ V/m

10^{-7} A/m²
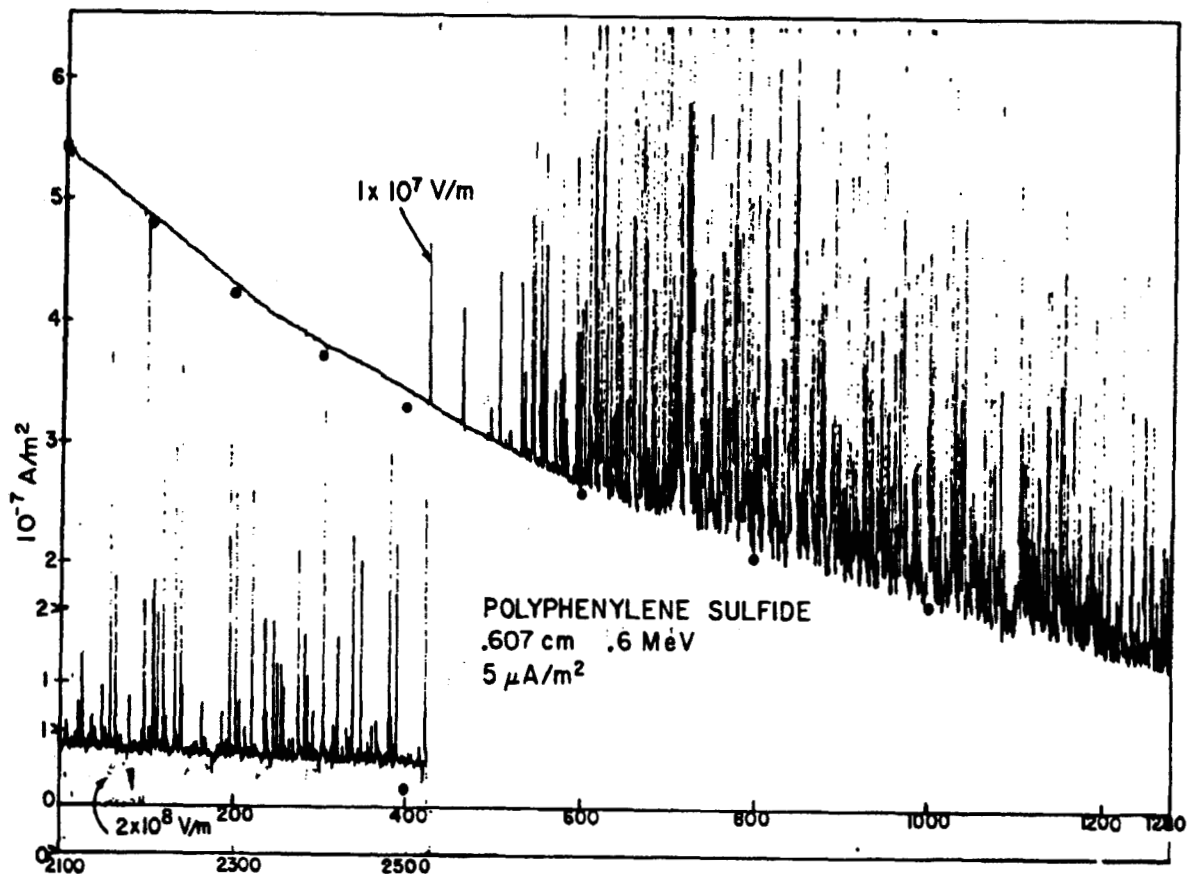
THE PULSING RATE IS DRAMATICALLY INCREASED IN SAMPLES COMPOSED OF
FIBERGLASS REINFORCED MATERIAL. THE SHARP ENDS AND DIFFERING
CONDUCTIVITY OF THE FIBERS INITIATE LIGHTNING BOLTS MOST EASILY. EVEN
THOUGH MANY PARTIAL DISCHARGES ARE OCCURRING, NEGLIGIBLE CHARGE IS
LOST FROM THE INTERIOR OF THE INSULATOR.

Note: High energy electron irradiations generally produce field strengths at a maximum of 2×10^{6}
V/cm. At that maximum level discharge pulses occur often, several per hour or per minute. More
typically one finds fields at about 2×10^{5} V/cm and pulsing is less frequent. [3] The fields reach this
steady state because the electrons also excite conductivity in the insulator.

SECOND BREAKDOWN PROCESS
A BURST OF GAS
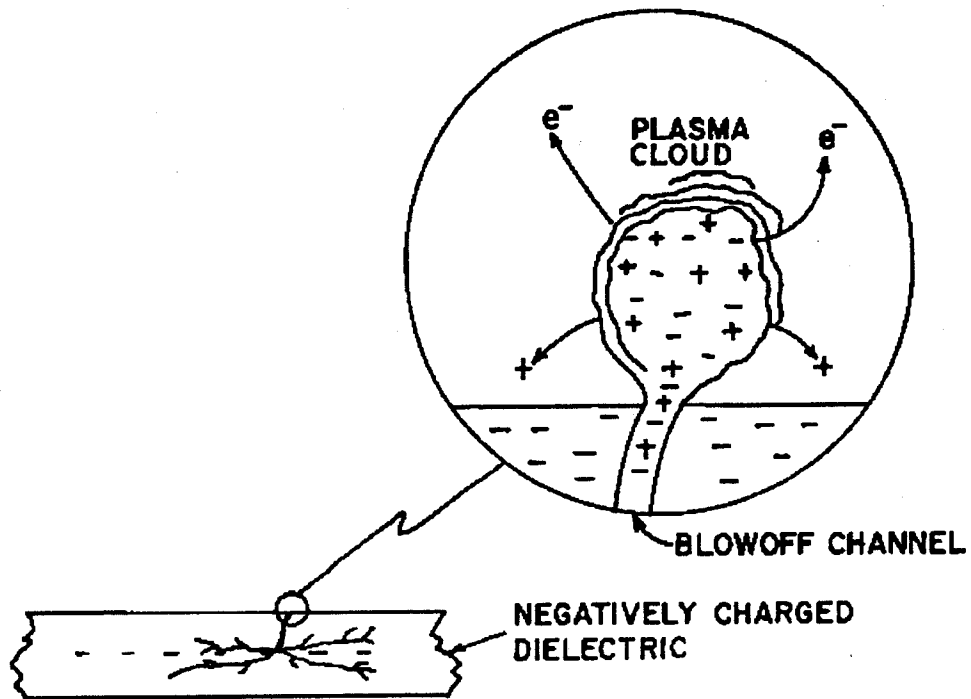
This figure depicts the fact that the plasma channels created by a discharge tree are hollow and the material was turned into an ionized gas to escape the solid. The gas expands from a density of perhaps 1000 in the channel to the ambient density in the vacuum outside the sample.

WHEN THE LIGHTNING BOLT EXTENDS OUT OF THE INSULATOR SURFACE, ITS BURST OF GAS AND PLASMA CAN INTERACT WITH EXPOSED ELECTRODES TO SHORT OUT A POWER SUPPLY. HERE WE SEE "CLOUDS" OF PLASMA GAS DRIFTING FROM AN IRRADIATED INSULATOR TO CONNECT TO ELECTRODES AND POWER SYSTEMS. ONCE CONNECTED, HUNDREDS OF AMPERES ARE SEEN TO FLOW, EVEN WITH LESS THAN 100 VOLTS. [4] THE CURRENT IN THE PLASMA GAS IS PROBABLY OF THE TOWNSEND/PASCHEN TYPE. [1]

The clouds expand at approximately 10^6 cm/sec, hot gas thermal velocities. Significant, but smaller currents are associated with the electrons which escape from the plasma and accelerate to high velocity in the vacuum electric fields. Avalanching in the gas provides a nearly endless supply of current when the electrodes continue to generate further gas. [1]
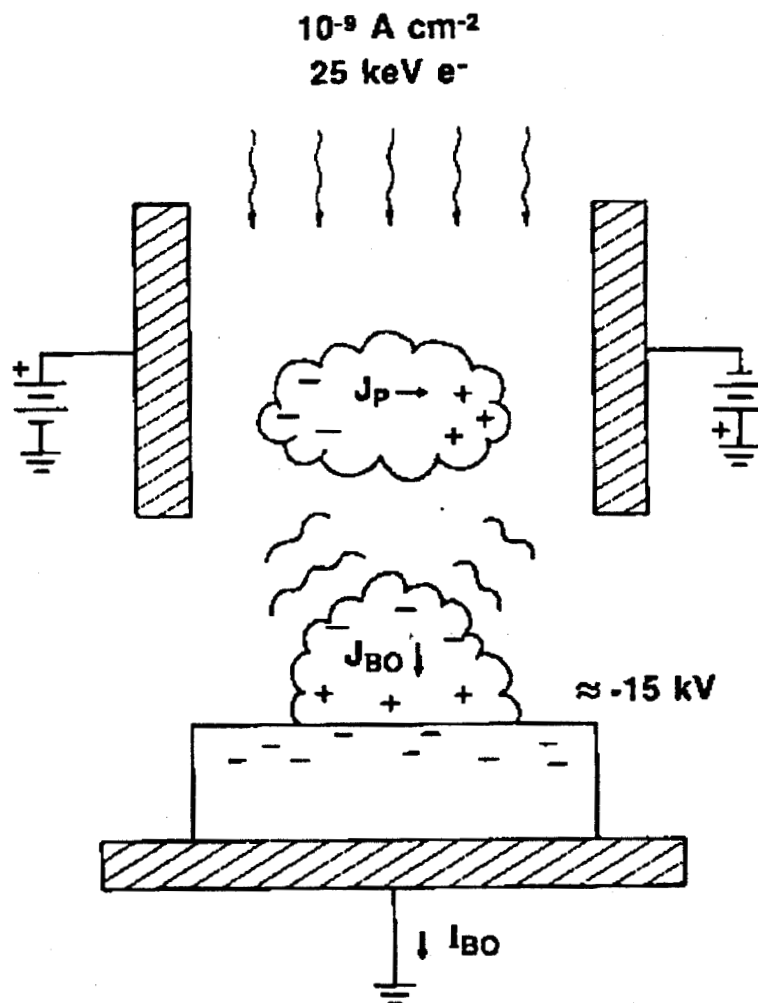
THE BATTERIES DRIVE CURRENT THROUGH THE PLASMA GAS CLOUD, I_P, AT HUNDREDS OF AMPERES. BATTERY VOLTAGE IS V_P. The batteries were high impedance so the current, I_P, stopped when the 2-microfarad capacitors across the batteries became discharged. Plasma current pulses were easy to generate for voltages from 100 volts, and up. One pulse was seen at V_P=50 volts. The inter-electrode spacing was 0.75 cm., and approximately 1 cm above the irradiated insulator.

The Paschen discharge process is not expected to occur below 100 volts. But the Paschen (or Townsend) process is theoretically analyzed with the assumption of a uniform non-ionized gas. Because our gas is highly ionized from the time of generation within the solid insulator, and has strong density gradients, one can not easily analyze the situation. Suffice it to say that severe current pulses have been seen at potentials as low as 50 volts in the laboratory [4], and undefined problems have occurred in space at approximately 80 volts.

Some gaseous lighting, voltage regulator tubes, and gaseous rectifiers work with less than 75 volts drop. One should not be surprised to see rare arcs at 50 volts in partial vacuum. Thus, one learns that the physics of gaseous arcs plays a role in failure of spacecraft solar arrays and other moderate voltage structures.
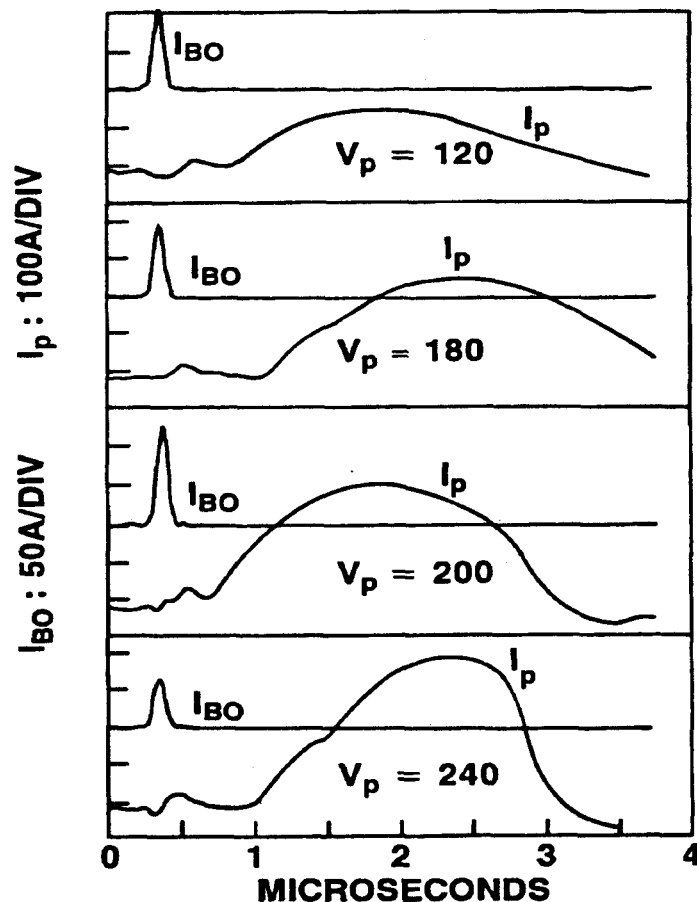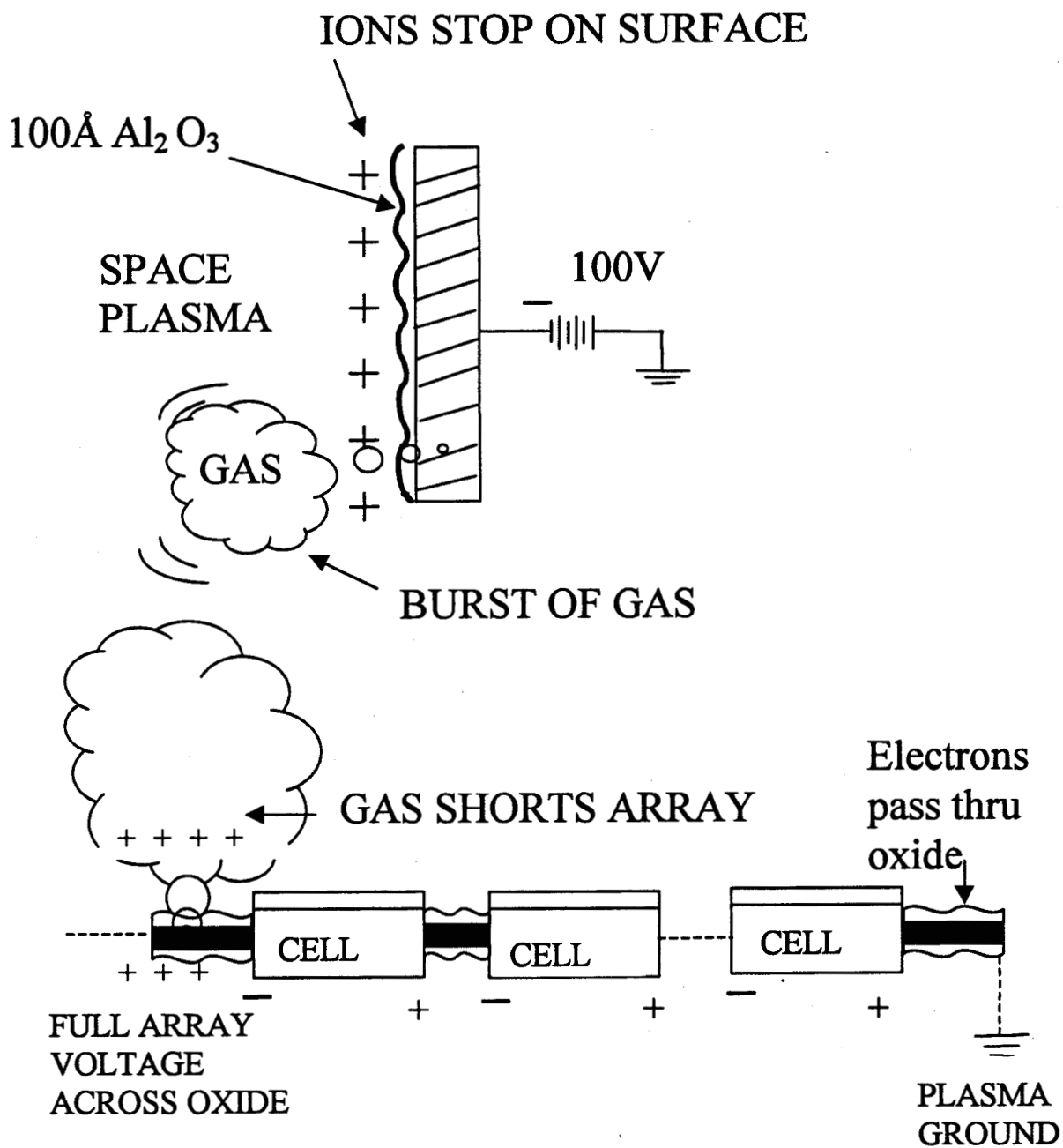
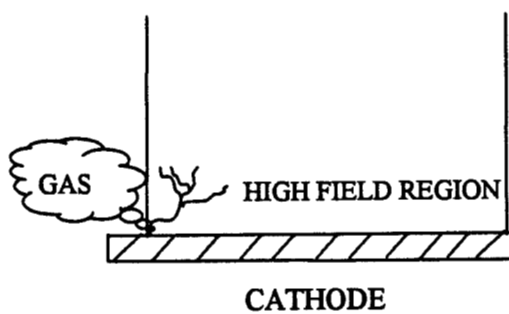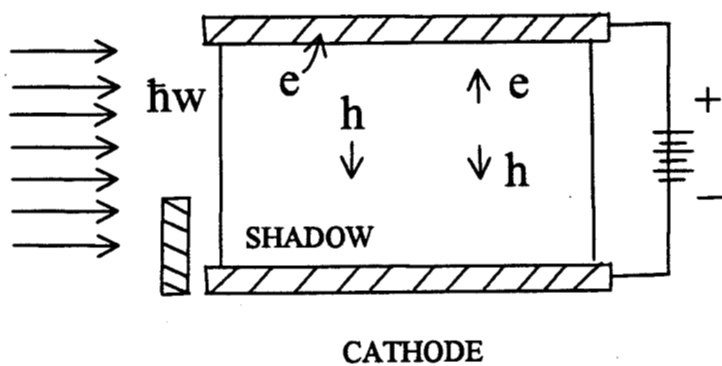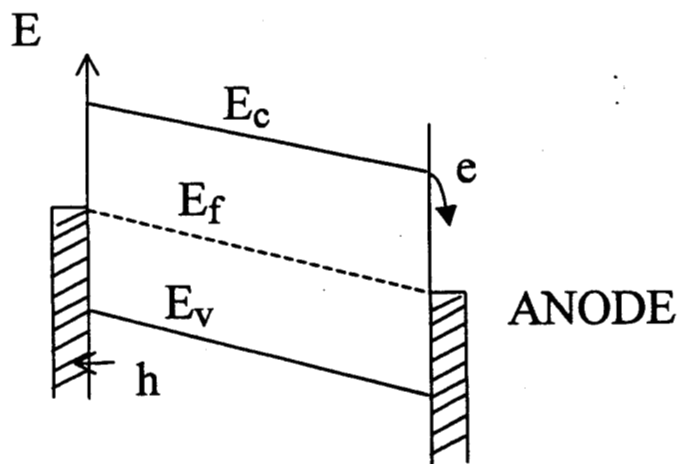## THIRD BREAKDOWN PROCESS - SPACE OR THRUSTER PLASMA ON THIN FILM INSULATORS

Aluminum naturally has 50 or 100 Angstroms of highly insulating oxide on its surface. If one biases the aluminum negatively with respect to ambient plasma, the positive ions collect on the surface of the oxide. Eventually the entire bias appears across the oxide. At 100 volts or more typical aluminum and anodized aluminum produce copious pulsing which eventually removes some of the oxide. The burst of gas may short nearby electrodes.

Positive bias accelerates electrons into the oxide, a situation which seems to be benign. Perhaps the electrons pass through the oxide without creating a threatening field in the oxide.

A spacecraft solar array generates a voltage. It is important that this voltage, acting with the space plasma, does not appear across a thin insulator. The thin insulator may burst and emit a pulse of gas which can short the solar array or other exposed voltage above 50 volts.

IONS STOP ON SURFACE

100Å Al_2O_3

SPACE
PLASMA

100V

GAS

BURST OF GAS

GAS SHORTS ARRAY

Electrons
pass thru
oxide

+ + + +

CELL

CELL

CELL

+ + +

FULL ARRAY
VOLTAGE
ACROSS OXIDE

+

+

+

PLASMA
GROUND

FOURTH BREAKDOWN PROCESS - CONDUCTION GRADIENT IN THE INSULATOR

E

E_c

e

E_f

E_v

ANODE

h

ℏw

e

h

e

h

SHADOW

+

−

CATHODE

GAS

HIGH FIELD REGION

CATHODE

Insulators are, simply, poor conductors. Within the insulator, the greatest field strength occurs across the best insulating region. Charge carriers slowly drift through an insulator. The moving carriers may exchange significant energy (1 eV) with specific atoms, defects or interfaces and slowly change the properties of the material. Carrier injection or loss at electrodes can change the insulator conduction properties. As a result, after years of operation, the insulator may develop local fields of 10^6 V/cm even though most of the insulator has fields less than 10^5 V/cm.

Shadows and sunlight combine to produce strong gradients in conductivity. The largest field strength will occur in the shadowed regions.

Current is carried from the insulator to the cathode by the capture of an electron from valance states in the metal as the hole in the insulator arrives at the cathode. This process is generally slow as it is unlikely that electron levels in the metal line up with the insulator hole levels. Often, the electric field must rise to large levels at the cathode in order to force conduction at the interface. At the anode, conduction electrons must make a transition to enter the anode. Thus, there is often a conduction gradient at both electrodes.

A discharge lightning bolt may initiate in the high field region. By itself, that is no problem. But if the bolt passes fully between two electrodes, they can be short-circuited by the plasma in the bolt. Once started in a high field region, the bolt may continue to propagate through a region of lower field. A bolt may issue a burst of plasma gas into vacuum, and thereby short a high voltage solar array with exposed electrodes.

Resetting fuses would be useful on solar cell arrays. The arc will quench if the current-voltage product is forced to be low. The insulator and the array will survive a brief arc. But an arc can be sustained at one ampere and thirty volts by the continued emission of gaseous material from the electrodes and nearby insulator. One must protect any source of power which exceeds roughly 25 watts with initial voltage above 50 from connection with a burst of gas between close spaced electrodes.

DS1 SOLAR ARRAY ARC PROBLEM

The DS1 solar array can achieve up to 120 volts. It must work in its own plasma environment generated by its ion engine. It will fly briefly in the Earth's radiation belts, but not long enough to produce an arc from high-energy electrons. The array bus bar insulation can experience graded conductivity through thermal gradients and sunlight shadowing. Prior to making a repair, the bus bars were exposed to the plasma, at which point there is an interface between insulator and biased metal. The insulator, right at the interface between insulator and metal, can act as a thin Al_2O_3 oxide acts on aluminum. The negative bus bar voltage and the space plasma can act to generate a high electric field at the edge of the insulator to produce a burst of gas. The full 100 volt drop appearing between the two bus bars exposed to space, and spaced only 2 to 3 mm apart, will be shorted by the gas burst.

The conditions for occurrence of a damaging arc were evident on DS1. Breakdown processes 2, 3 and 4 were likely to occur on DS1. Process 1 might also occur if DS1 spent more time, greater than one day, in the Earth's radiation belts. The solar array has more than sufficient power to maintain the arc until the bus bars burn away. The array was repaired by covering the exposed bus bars with thick insulating paint. The burst of plasma gas that the insulators may emit is prevented from connecting to the bus bars.

There are extensive regions on the arrays where the three breakdown processes can be initiated, but not on the bus bars. Only the bus bars carry enough power to sustain an arc (based on recent results from NASA Lewis). Each subsection of the array provides ten watts, or less, when loaded down to 25 volts and is presumed incapable of maintaining an arc. An arc in any subsection is diode-isolated from the bus bars. The number and complexity of problem points is so great that there is no possibility of easily repairing them. One expects the occurrence of occasional pulses on the arrays without producing damage. One hopes that the sparse information on sustaining arcs is sufficient to act as a guide at this time.

REPAIR OF THE ARCING HAZARD ON DS1 SOLAR ARRAYS. THE LEFT PANEL IN THE FIGURE DEPICTS THE BUS BARS (in cross section) PRIOR TO THE REPAIR. THE REPAIR SHOWN IN THE RIGHT PANEL CONSISTS OF THE APPLICATION OF INSULATING PAINT TO THE EXPOSED BUS BARS. THE PAINT PREVENTS THE BURSTS OF GAS FROM SHORTING TO THE BUS BARS.
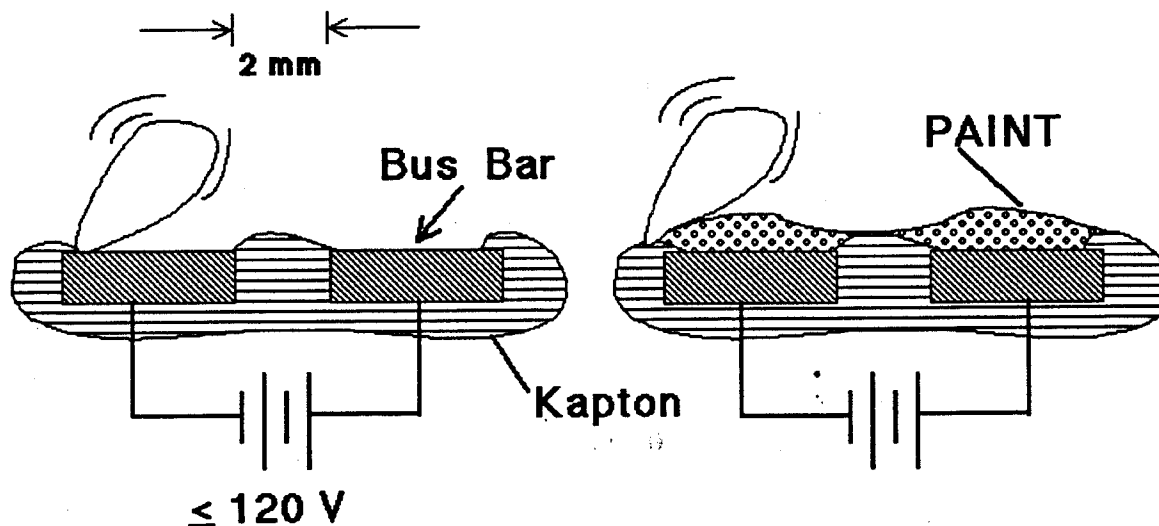
PARTIAL SUMMARY:

FOUR PHYSICAL PROCESSES FOR THE BREAKDOWN OF SOLAR ARRAYS HAVE BEEN DESCRIBED.

H.E. Electron Accumulation in the Insulator, Conductive Plasma Trees (Lightning)

Burst of Gas from any Source

Plasma Interaction with Thin "Oxides" on Conductors (gas burst)

Conduction Gradients in the Insulator (gas burst, or tree)

NEXT:

ELECTROMAGNETIC PULSE FROM ELECTRONS BURIED DEEP IN THE SPACECRAFT ELECTRONICS IS DISCUSSED.

PROBLEM (CASE) II: DEEP DIELECTRIC CHARGING

Electrons penetrate deep in insulators, even inside electronic boxes. (Circuit Boards, Wire Insulators, Connectors, etc.)

1 – 100 Volt Pulses Common

2 kV Pulses with Special Geometry

The Insulators may discharge with a spontaneous pulse.

Physics and lab Experiments can be frightening, 100 volt pulses occur, but do they occur in space?

Spacecraft don't fall out of the sky. They mostly survive. Catastrophic pulses are rare.

Circuits are complex, pulse energy distributes to many circuits.

AT THIS TIME, PHYSICS IS NOT MUCH HELP, THE COMPLEXITIES ARE OVERWHELMING. ONE MAY DEFER TO A DESIGN GUIDELINE BASED ON IN-SPACE TESTS. [5,6]

The calculation of voltages and fields inside electronic enclosures due to radiation-induced space charge is complicated. Almost nothing is known about it. There are indications that secondary electron emission from internal surfaces mitigates the magnitude of the threat. [7] Yet spontaneous discharges inside enclosures is certainly threatening. One can conceive of arrangements of materials where kilovolt pulses occur. [Designers should know enough to avoid these arrangements. However, the kilovolt pulse phenomena was first seen in a standard enclosed antenna design for which solutions are not yet proven.

If it is possible to provide sufficient shielding, one can reduce the probability of occurrence of a pulse to less than one per spacecraft lifetime. The graph below is the only data which allows one to do the estimation of pulse rate. For typical electronic boxes, one would shield to this level only where especially sensitive circuits reside (10 volt, 10 nsec.pulse sensitivity). Most of the pulses are in the 1-10 volt range. [8]

THE IN-SPACE TESTS ON A SPACECRAFT COUNTED PULSES OF ONE VOLT PEAK OR LARGER.
ON-BOARD SPECTROMETERS MEASURED THE ELECTRON FLUX IMPACTING THE INSULATORS.
THE PULSE RATE CORRELATES WITH, AND CAN BE ESTIMATED FROM THE H.E. ELECTRON FLUX.

ONE MAY DESIGN SHIELDING TO REDUCE THE FLUX TO AN ACCEPTABLE PULSE
RATE
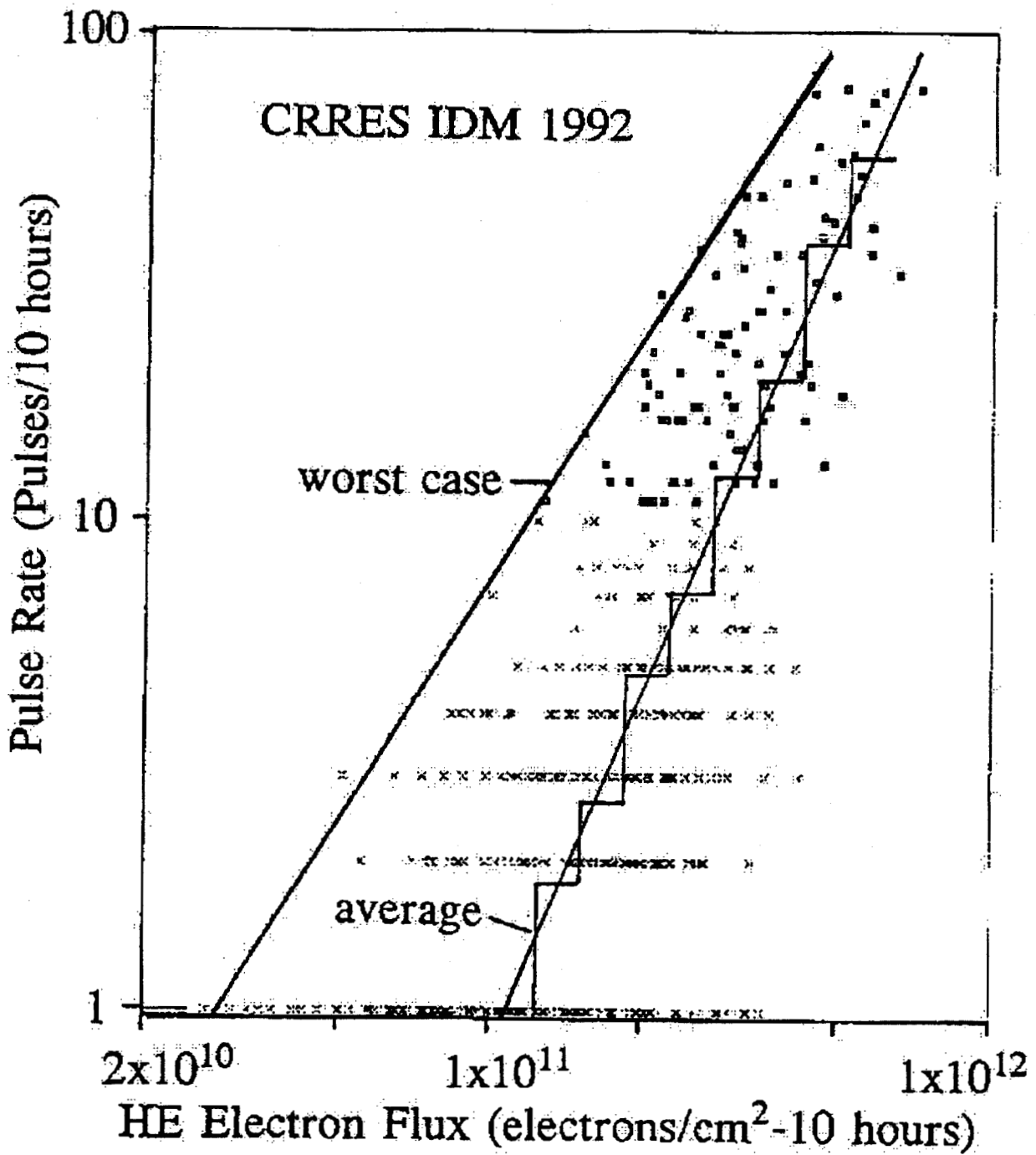
PROBLEM III

RADIATION-INDUCED DEGRADATION OF
GALILEO GYROSCOPE ELECTRONICS

HINT:

ELECTRIC FORCES HOLD MATERIAL TOGETHER, OR BREAK IT APART.

MECHANICAL FORCES ARE IMAGINARY, THEY DO NOT EXIST.

BY THINKING ELECTRIC, WE CAN UNDERSTAND THE RESPONSES OF MATERIAL TO PLASMA, RADIATION AND ELECTRIC FIELDS

THEREFORE, even structural defects can be altered or annealed by electrical methods.

High-energy radiation displaces single atoms in material via electronic and nuclear interaction. The result in semiconductors and insulators is most interesting. Some of the displacements result in the ultimate creation of point defects such as impurity-vacancy pairs, or impurity-impurity pairs. Some of these point defects are electrically active and strongly alter the operation of devices.

Consider one atomic plane. If one of 200 atoms in the plane is charged, this plane alone produces an electric field strength near breakdown and thereby alters the electrical operation of any device with which it is associated. Very few defects are required to alter device performance. It has been difficult to determine the structure and the processes of formation of the active defects because physical/chemical studies often require much higher concentrations of the species. A few of the species are well known.

By application of electric field one may shift the Fermi-level and alter the activity of defects. One may even cause some defects to "anneal', or to migrate and change into other defects. Further, introduction of electrons or holes into the region of the defects can enhance their rate of annealing, alteration or formation. [9-11]

Understanding of the defects is not so firm that one knows the life of a defect. It remains available to the reliability physicist that many of the active defects can evolve as a function of the environmental stresses placed upon them. We have yet to explore the possibility that we can alter the defects by changing the operation of the electrical devices in order to prolong useful life of devices under space radiation. The following physics liberates one's mind to think clearly about radiation effects in material. Specifically, defects are not mechanical things, they are electrical both in themselves and in how they cause problems in semiconductors.

Radiation-induced Defects are created by an electrical interaction, not a mechanical force. In semiconductors and insulators there is sufficient energy available in the electronic conduction states (1 eV) to alter the defects. For many cases, after radiation has modified the material by creating defects, one can change the defects by modifying the electrical parameters of the device.

Electronic devices contain many radiation sensitive structures: gate oxides, passivation oxides, conducting channels, p-n junctions, isolation junctions, surfaces. When each of these structures is studied alone, it becomes clear that the voltage bias applied to the structure during irradiation strongly affects the outcome of the test. This phenomena will be described using the well known example of the irradiated MOS capacitor. The generic argument can be carried to most other electro-chemical structures as well, including p-n junctions, insulator-electrode interfaces, etc.

ONE OF THE CAUSES COULD BE
CHARGE BUILD-UP IN OXIDE FROM RADIATION
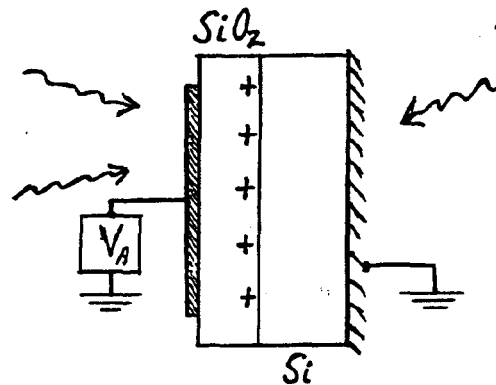
As the radiation of the silicon and silicon dioxide MOS capacitor structure proceeds, trapped hole charge accumulates near the silicon/silicon dioxide interface and in the bulk of the oxide. The accumulation proceeds most rapidly with high positive gate bias. A similar charging process occurs in passivation oxides elsewhere in the device. The Galileo device is a JFET, not a MOS device. Therefore oxide charging in this device is by passivation oxide only, but the concepts are similar.
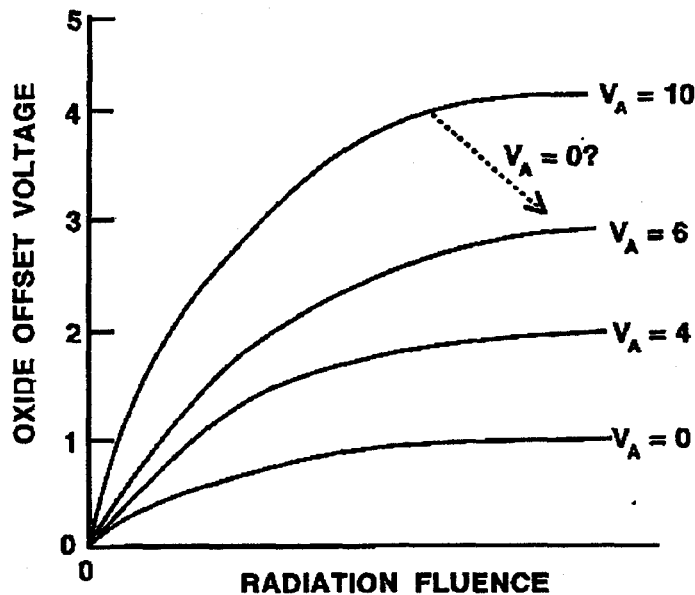
Generic Figure of Oxide Charging or Other Radiation Effect.

Galileo's gyroscope electronics was beginning to drift, and caused the self checks within the autonomous guidance system to produce costly "safe holds." The anomaly tiger team decided that a specific place in the circuit was leaking current either through a capacitor or through a semiconductor device. The leakage caused the circuit scale factor to rise from the nominal 1.00. The measure of the scale factor is the measure of the leakage, there is no direct measure of leakage current.

the problem on Galileo may also relate to effects in a p-n junction. In p-n junctions the first irradiation can introduce significant defects. A second irradiation under differing conditions can remove some of the previous defects. The device can be annealed by radiation. The annealing can be adjusted by controlling applied bias during the irradiation. [9-11]

The leaking junction in the JFET device is a reverse biased p-n junction. Defects accumulate most rapidly in a junction when it is reverse-biased during irradiation. Junction leakage current is caused predominantly by defects in the junction. It has been shown that the accumulation is optimized in reverse bias because reverse bias slows the recombination-induced annealing of defects. [10]

Finally, there is a capacitor across the suspect junction. The capacitor might be leaking due to irradiation-induced arcing damage or some unknown cause.

THE GALILEO CURE:

THE ANOMALY STUDY WAS UNABLE TO IDENTIFY THE EXACT MECHANISM CAUSING THE FAILURE. BUT, FAILURE WAS MOST LIKELY LEAKAGE IN A JFET SWITCH. ANOTHER POSSIBILITY WAS LEAKAGE IN A CAPACITOR.

THE MECHANISM COULD BE PASSIVATION OXIDE CHARGING, P-N JUNCTION
DEFECTS, CHARGED SURFACE STATES, OTHER?

IT WAS REASONABLE TO PRESUME THAT THE PROBLEM ORIGINATED IN A
STRUCTURE THAT HAD NEARLY THE WORST CASE BIAS DURING PASSAGE IN THE
RADIATION BELTS. The structure probably would not have been as seriously damaged if it had
not been so-biased.

ZERO-BIAS IS RARELY THE WORST CASE. For the oxide charging and the leaking capacitor
problems, zero bias may be the least damaging case. For the p-n junction, zero bias is one of the
lesser damaging conditions.

THEREFORE, ZERO-BIAS DURING THE RADIATION BELT PASSAGE MIGHT BE ABLE
TO ANNEAL THE FAILING STRUCTURE OF THE JFET SWITCH.

Electron-hole recombination at a defect liberates enough energy to sometimes "anneal" the defect.
Continued irradiation injects copious electron hole pairs thereby annealing the damage previously
introduced. This thesis has been proven for p-n junctions. [9-11]

Consider the curve in the oxide charging graph for applied voltage of 10 volts. After some
irradiation time, the oxide is highly charged. One can then turn off the applied gate bias voltage
while the space radiation continues. Continued irradiation of the MOS structure under zero bias
may be able to redistribute the trapped-hole charge to the condition produced under zero bias alone.
The curve labeled V=0? indicates such postulated behavior.

Finally, allowing a leaky capacitor to rest might allow it to recover some of its insulation (unlikely,
but one can hope).

THE CURE IS TO APPLY ZERO-BIAS DURING PASSAGE THROUGH THE RADIATION
BELTS. THAT THE CURE WORKED IS SHOWN BY THE GRAPH OF GALILEO GYRO
SCALE FACTOR RECOVERY. THE SCALE FACTOR CORRECTLY REMAINED AT 1.00
UNTIL ORBIT 12 WHERE ACCUMULATED RADIATION EFFECTS FINALLY CAUSED
THE SCALE FACTOR CIRCUITS TO PRODUCE AN ERROR. Although leakage was probably
increasing continuously since the insertion into Jovian orbit, the circuit did not generate an incorrect
scale factor until orbit 12. Substantial leakage is required to generate an incorrect scale factor.
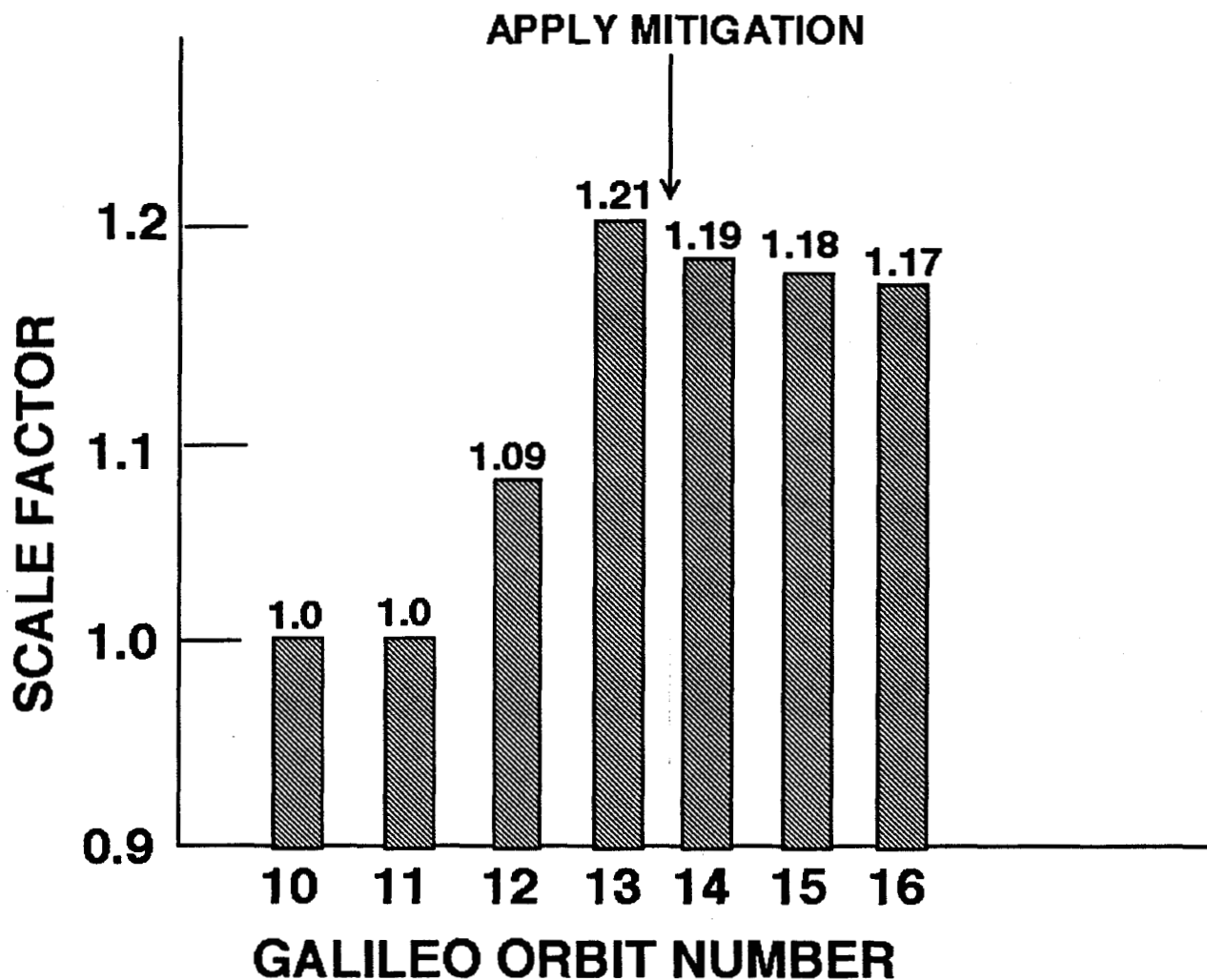
APPLY MITIGATION

The mitigation has been applied to all orbits after #13. The mitigation consists of applying zero bias to all components during half of the two days passage in the radiation belts. The "half belt" time of zero bias apparently removes slightly more damage than the "half belt" time of normal bias generates. The spacecraft has been adjusted to operate with the new scale factor. Operational constraints for the spacecraft limited the mitigation to apply zero bias for only half the time in the radiation belts.

LESSONS FROM GALILEO

Radiation effects are known to be very complex. This experience with Galileo proves that one can make use of the complexity.

The old process, of testing to parameter out-of-spec condition, only works if one tests worst case and if one can find devices that won't fail at the worst case. What do we do if no device can be found that passes this test?

Under radiation devices don't fail by crashing, they slowly drift into a problem area.

We should look for ways to control the drift and steer it away from a problem area.

The information from the semiconductor defects community (which is separate from the radiation testing community) can be better applied to solve the problem of radiation damage in electronic devices.

Future systems can be flown under a radiation tolerance philosophy. But, more complete device testing would need to be done in order to devise the in-flight tolerance schemes.

CONCLUSIONS – OPINIONS

CONCLUSIONS
ELECTRICAL WIRING SUCH AS SOLAR ARRAYS EXPOSED TO SPACE WITH MORE THAN 50 VOLTS ARE IN JEOPARDY OF ELECTRICAL BREAKDOWN BY SEVERAL MECHANISMS. EXTENSIVE WORK IS NEEDED TO SOLVE THE DIVERSE PROBLEMS.

ELECTROSTATIC CHARGING BY H.E. ELECTRONS IN SPACE IS A SERIOUS THREAT INSIDE SPACECRAFT ELECTRONICS. THE FAILURE EVENT RATE AND THREAT MAGNITUDE HAVE YET TO BE QUANTIFIED FOR GOOD ENGINEERING PRACTICE.

THE PHYSICS OF RADIATION EFFECTS IN SEMICONDUCTORS IS NOT WELL UNDERSTOOD, AND THERE APPEAR TO BE SOME EFFECTS THAT MAY ALLOW US TO OPERATE A SPACECRAFT IN A RADIATION TOLERANT MODE BY NURSING IT THROUGH ILLNESS, AND EXTEND LIFE.

OPINIONS
Knowledge of physics allows one to find the root cause of some failures, and to determine the best path for avoiding the failure. (DS1 array bus bar fix)

Understanding the limitations of our present knowledge of physics is the key to guiding one to anticipate future failure modes, and to develop testable paths to solving failures. (Use radiation to actually remove defects, on Galileo)

Some phenomena are still a mystery to physicists, and by acknowledging the mystery, one is able to move ahead in engineering by determining the worst case situations. (electrostatic breakdown of insulators)

REFERENCES: No attempt has been made to provide complete references. More complete references can be found in these referenced works.

1. H. Raether, Electron Avalanches and Breakdown in Gases, Butterworths, London, 1964
2) A. R. Frederickson, S. Woolf and J. C. Garth, "Model for Space Charge Evolution and Dose in Irradiated Insulators at High Electric Fields," IEEE Trans. Nuc. Sci. 40, No. 6, 1393-1401, Dec., 1993.
3) A. R. Frederickson, "Electric Discharge Pulses in Irradiated Solid Dielectrics in Space", IEEE Trans. Elect. Ins. EI18, 337-49 (1983)
4) A. R. Frederickson, Leon Levy and C. L. Enloe, "Radiation-induced Electrical Discharges in Complex Structures," IEEE Trans. Electrical Insulation 27, No. 6, 1166-87, Dec. 1992.
5) A. R. Frederickson, "Upsets Related to Spacecraft Charging," IEEE Trans. Nuc. Sci. 43, 426-441, April, 1996.
6) A. R. Frederickson, "Method for Estimating Spontaneous Pulse Rate by Insulators Inside Spacecraft," IEEE Trans. Nuc. Sci. 43, 2778-82, Dec. 1996.
7) A. R. Frederickson, "Radiation-Induced Voltage on Spacecraft Internal Surfaces," IEEE Trans. Nuc. Sci. 40, No. 6, 1547-54, Dec. 1993.
8) A. R. Frederickson, E. G. Holeman and E. G. Mullen, "Characteristics of Spontaneous Electrical Discharging of Various Insulators in Space Radiations," IEEE Trans. Nuc. Sci. 39, 1773-82, December 1992. Early portions of this paper have been published in Proceedings XVth International Symposium on Discharges and Electrical Insulation in Vacuum, IEEE #92CH3192-2, pp 590-4, Darmstadt, Germany, 1992; in The Proceedings IEEE Int'l.Conf. on Solid Dielectrics, Sestri-Levante, Italy, June 1992; and in the Proceedings of the 1992 IEEE Conference on Electrical Insulation and Dielectric Phenomena, Oct. 1992.
9) A. R. Frederickson and P. J. Drevinsky, "Defect Concentration Gradients at Semiconductor Junctions," in Defects in Semiconductors, Eds. H. Heinrich and W. Jantsch, Materials Science Forum, Vols. 143-7, pps. 1403-8, Trans Tech Publications, Switzerland, 1993.
10) P. J. Drevinsky, A. R. Frederickson and D. W. Elsaesser, "Radiation-Induced Defect Introduction Rates in Semiconductors," IEEE Trans. Nuc. Sci. 41, No. 6, 1913-23, Dec. 1994. ***
11) A. R. Frederickson and A. S. Karakashian, "Capacitance-voltage measurement of charged defect concentration profile near semiconductor depletion zones," J. Appl. Phys. 77 (4), 15 Feb. 1995, 1627-34. ***